
Performance of Fermilab's electron cooling system

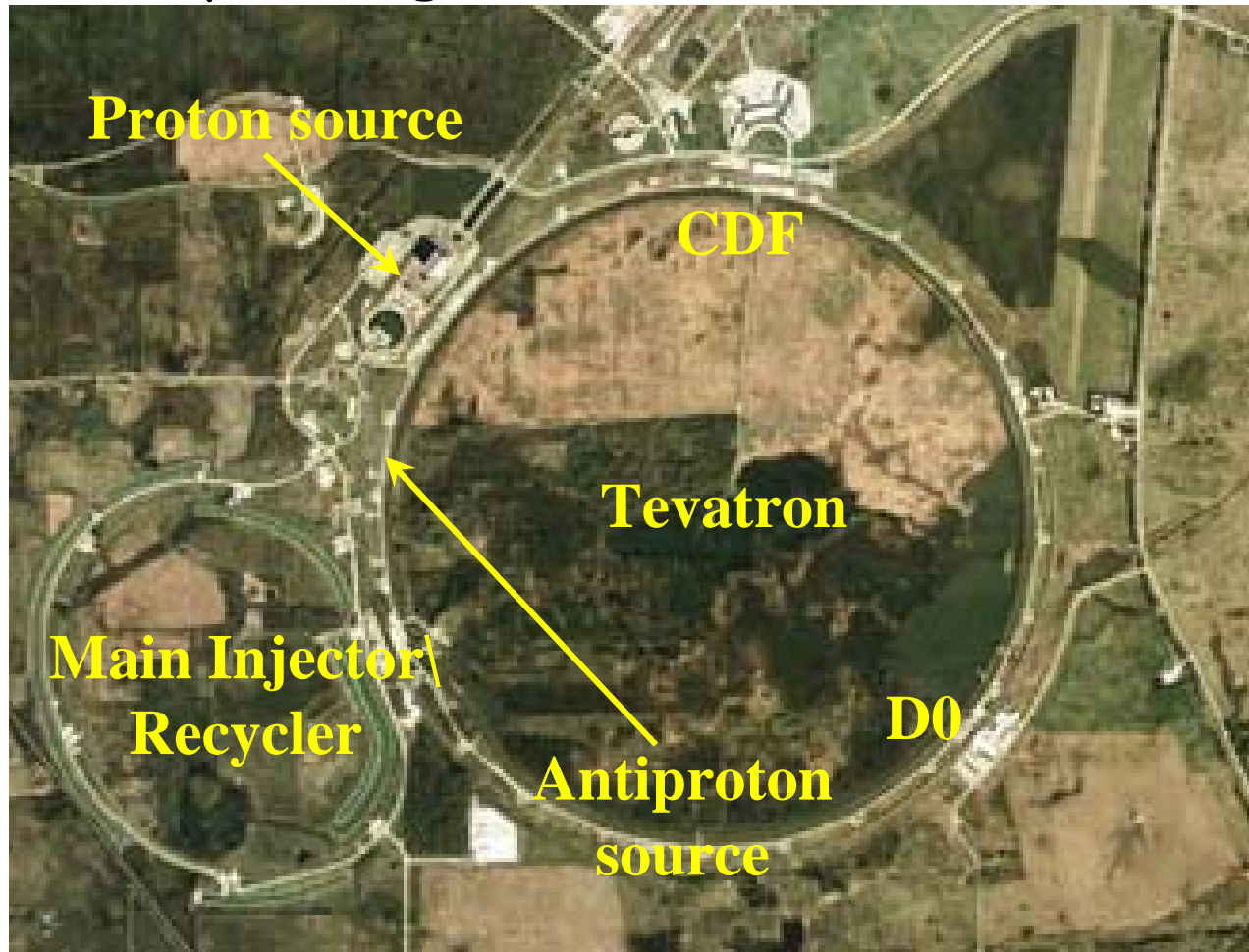
May 24, 2006
Sergei Nagaitsev



Fermi National Accelerator Laboratory

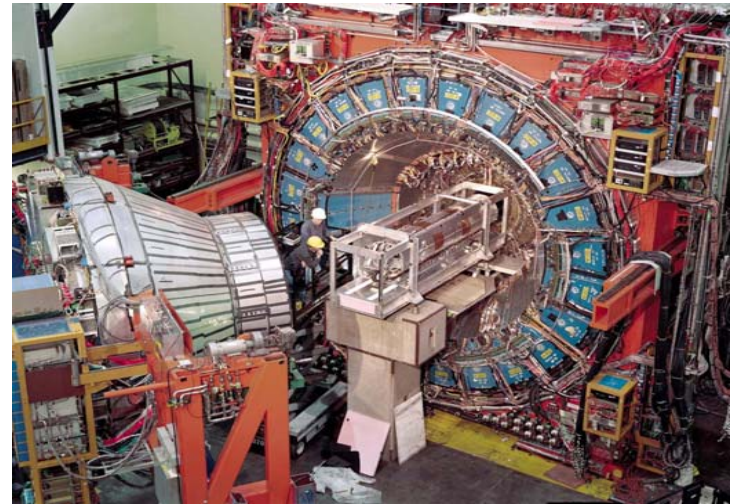
Fermilab Complex

- The Fermilab Collider is a Proton-Antiproton Collider operating at 980 GeV

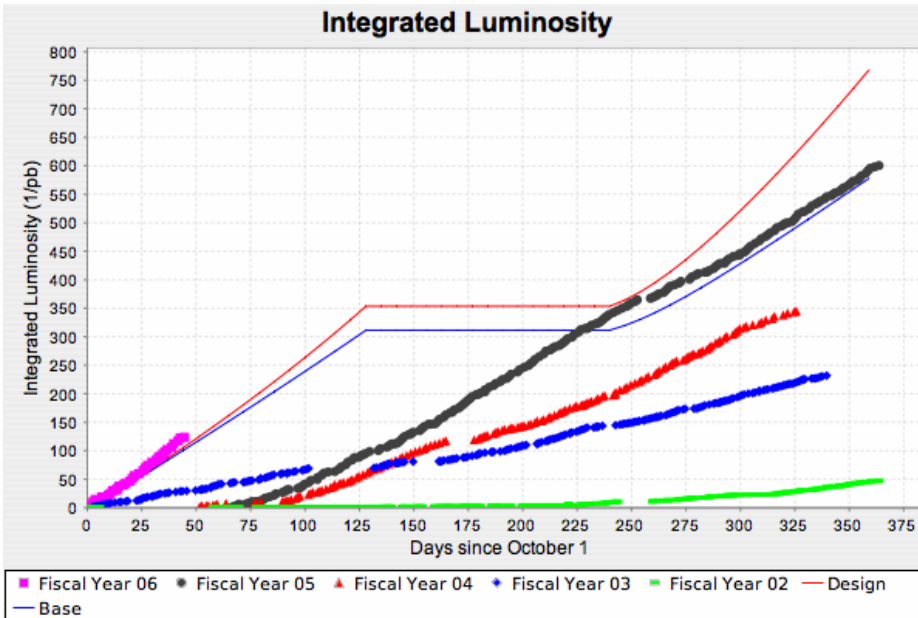


Tevatron Program

- Greatest window into new phenomena until LHC is on
- 1500 collaborators, 600 students + postdocs
- Critically dependent on luminosity
- Doubling time a major consideration



Tevatron: key is luminosity

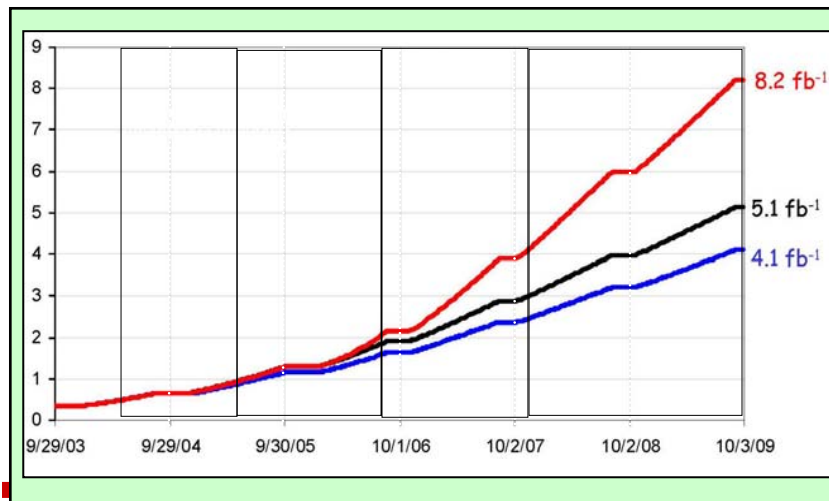


Luminosity history
for each fiscal year

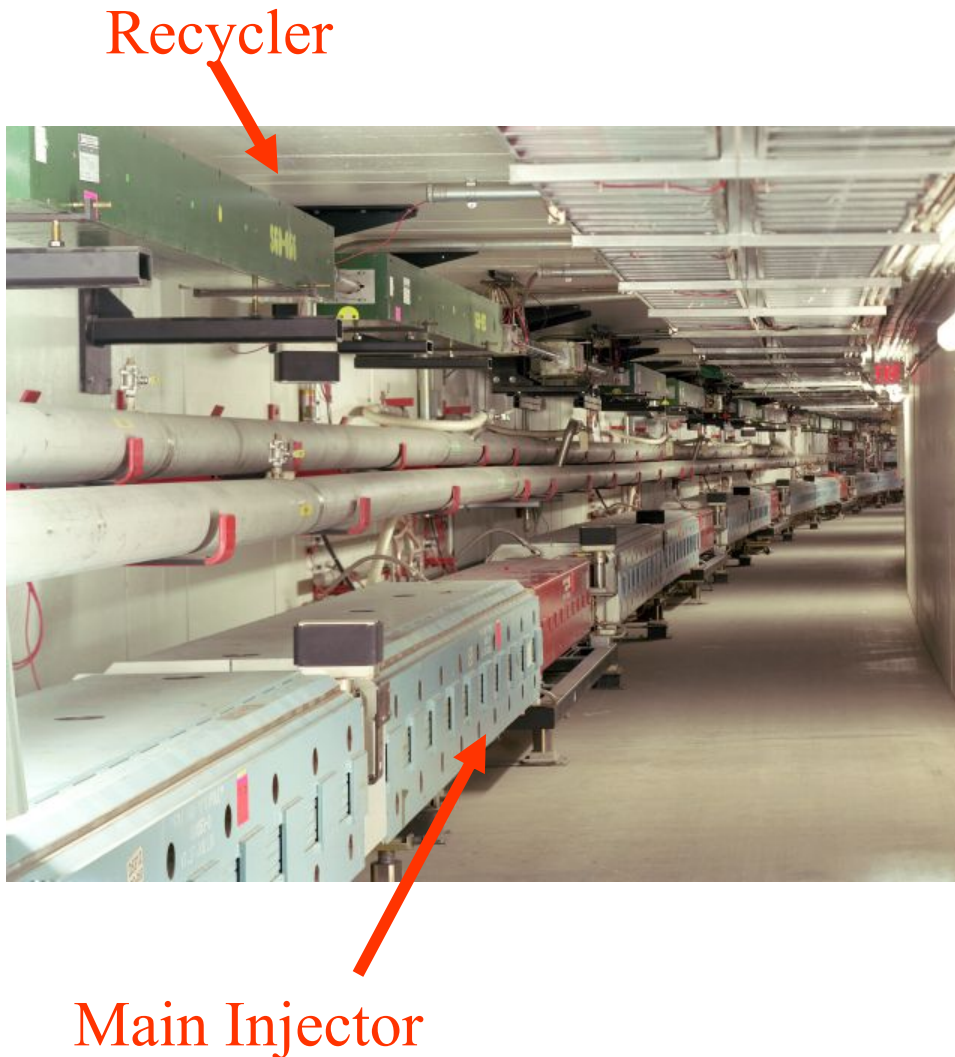
Integrated luminosity
for different assumptions

Top Line: all run II upgrades work

*Bottom line: none work
(pink/white bands show the
doubling times for the top line)*



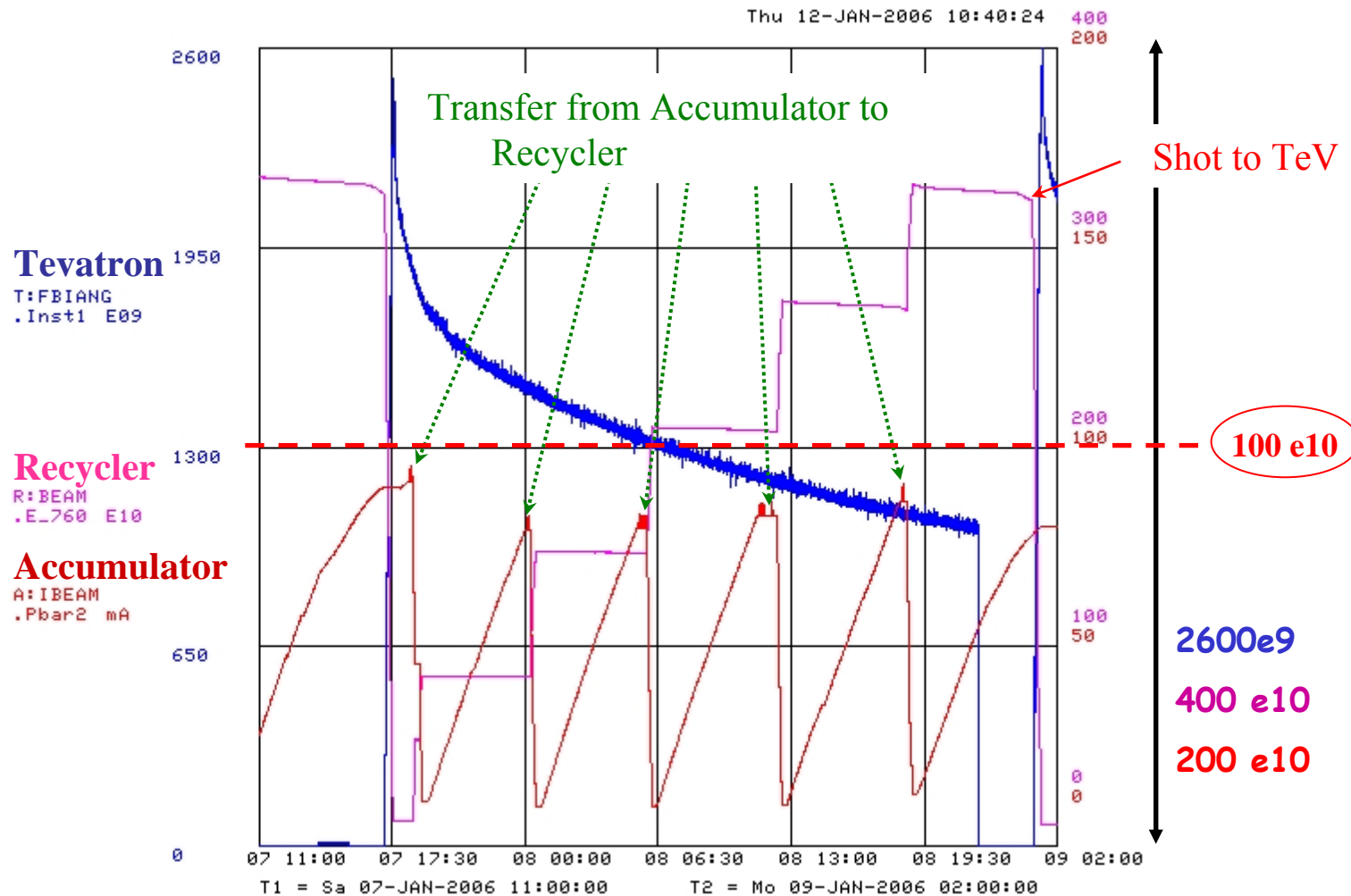
Recycler – Main Injector



The **Recycler** is a fixed-momentum (8.9 GeV/c), permanent-magnet antiproton storage ring.

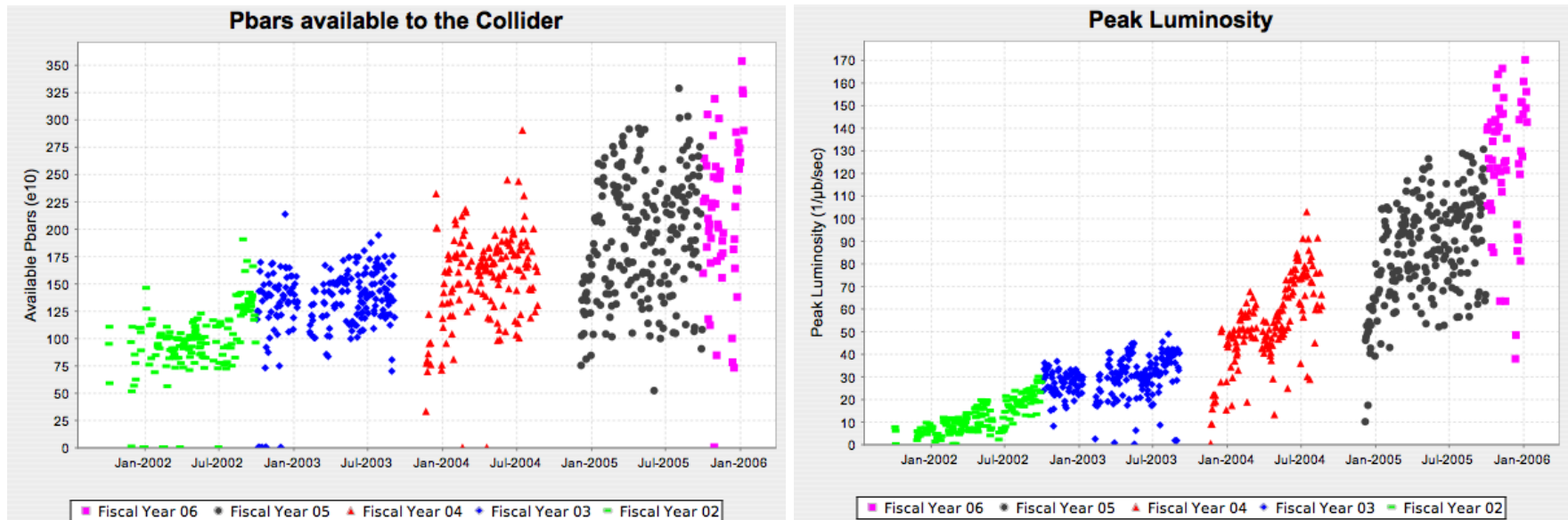
The **Main Injector** is a rapidly-cycling, proton synchrotron. Every 1.6-3 seconds it delivers 120 GeV protons to a pbar production target. It also delivers beam to a number of fixed target experiments.

Antiprotons **flow** (Recycler only shot)



Keep Accumulator stack $< 100 \text{ e10} \Rightarrow$ Increase stacking rate

Antiprotons and Luminosity



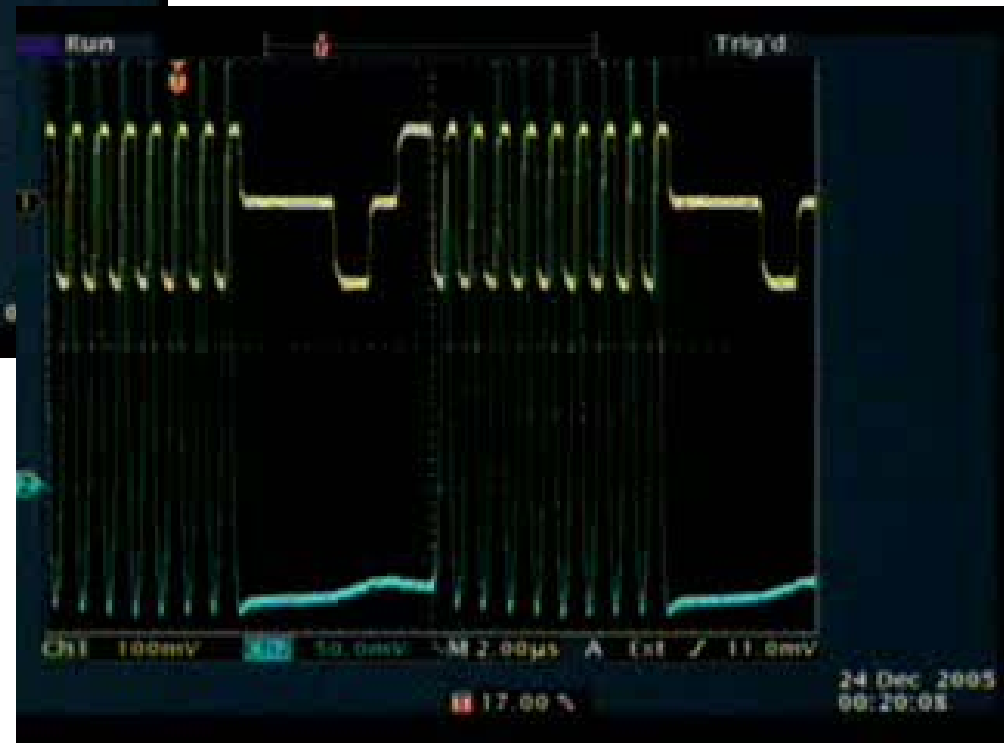
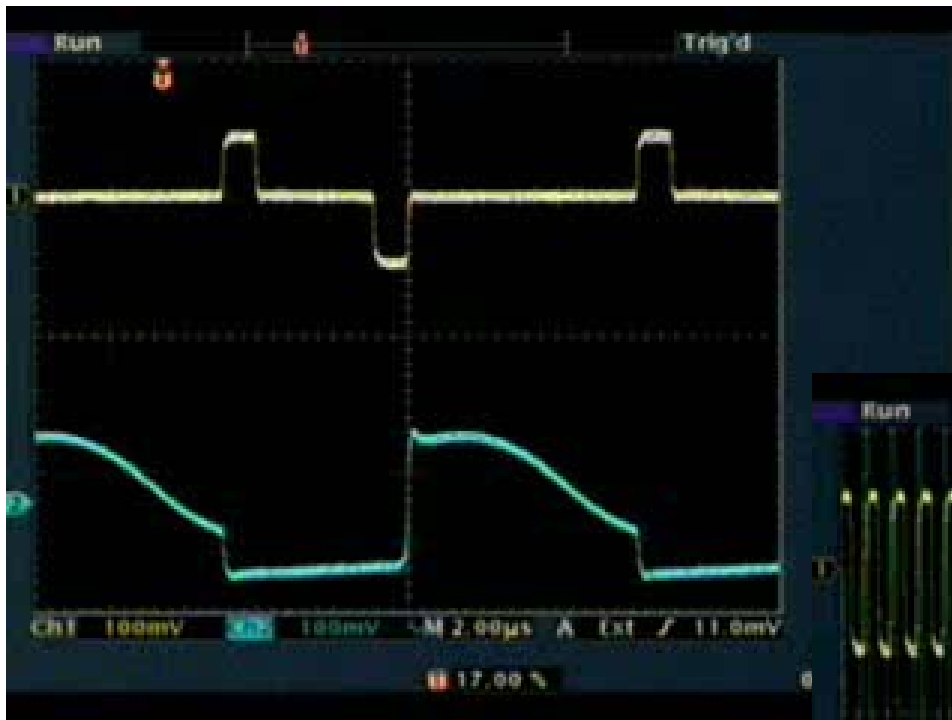
- The strategy for increasing luminosity in the Tevatron is to increase the number of antiprotons
 - Increase the antiproton production rate
 - Provide a third stage of antiproton cooling with the Recycler
 - Increase the transfer efficiency of antiprotons to low beta in the Tevatron

Beam Cooling in the Recycler

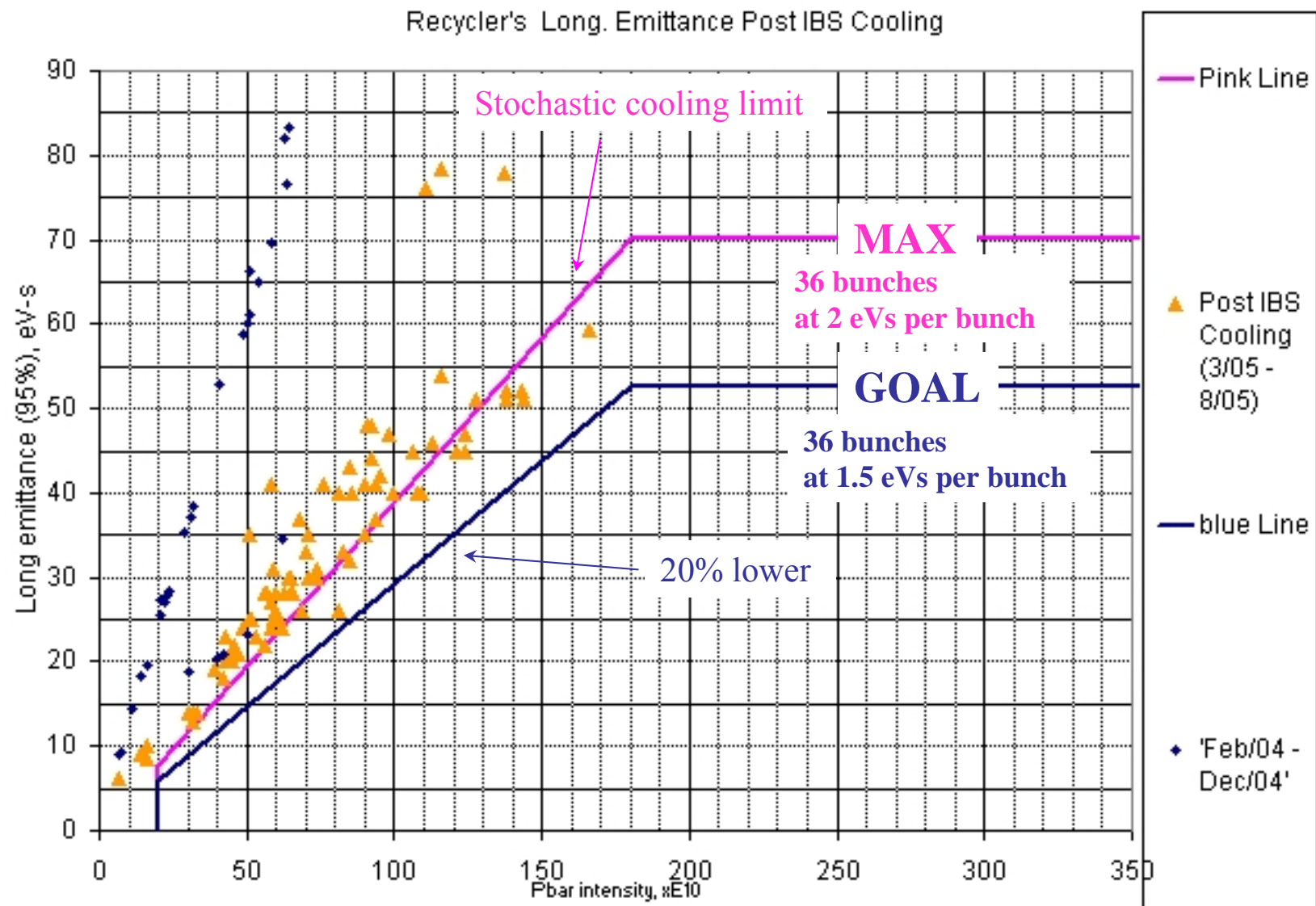
The missions for cooling systems in the Recycler are:

- The multiple Coulomb scattering (IBS and residual gas) needs to be neutralized.
- The emittances of stacked antiprotons need to be reduced between transfers from the Accumulator to the Recycler.
- The effects of heating because of the Main Injector ramping (stray magnetic fields) need to be neutralized.

Recycler beam is extracted in 9 batches, 6 eV-s each



Performance goal for the long. equilibrium emittance: 54 eV-s



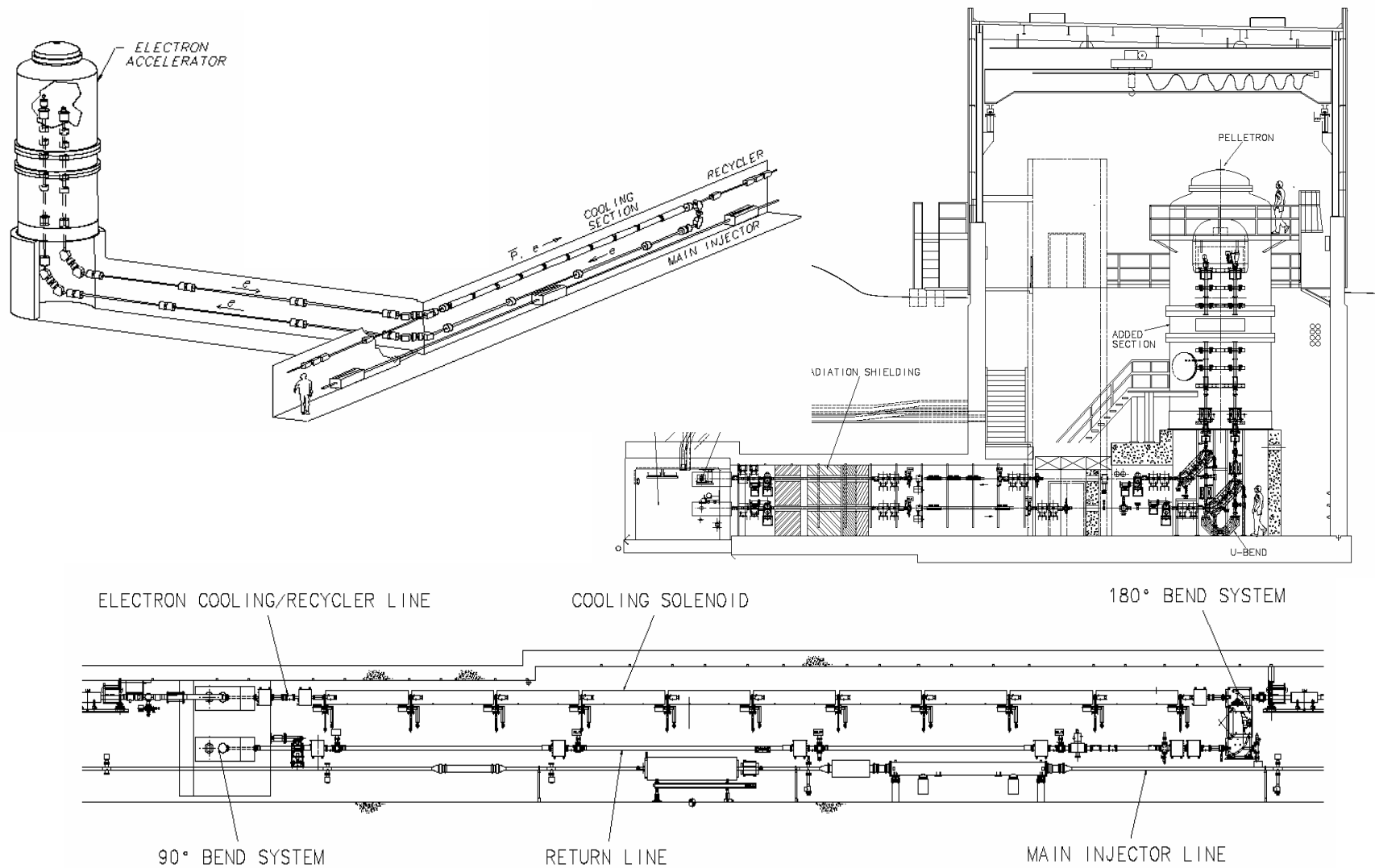
Recycler Electron Cooling

- The maximum antiproton stack size in the Recycler is limited by
 - Stacking rate in the Debuncher-Accumulator at large stacks
 - Longitudinal cooling in the Recycler
 - Stochastic cooling only
 - $\sim 140 \times 10^{10}$ for 1.5 eVs bunches (36)
 - $\sim 180 \times 10^{10}$ for 2 eVs bunches (36)



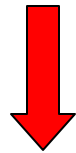
Longitudinal stochastic cooling
has been complemented by
Electron cooling

Schematic Layout of Fermilab's Electron Cooler



Electron cooling system setup at MI-30/31

Pelletron
(MI-31 building)



Cooling section
solenoids
(MI-30 straight section)

What makes the Fermilab system unique?

- It requires a 4.36 MV DC power supply. We have chosen a commercially available electrostatic accelerator. As a consequence we had to develop several truly new **beamline, cooling, and solenoid technologies**:
 - Interrupted solenoidal field: there is a magnetic field at the gun cathode and in the cooling section, but no field in between. It is an angular-momentum-dominated transport line;
 - Low magnetic field in the cooling section: 50-150 G. Unlike low-energy coolers, this will result in non-magnetized cooling - something that had never been tested;
 - A 20-m long, 100-G solenoid with high field quality
-

Electron beam design parameters

▪ Electron kinetic energy	4.34 MeV
▪ Uncertainty in electron beam energy	$\leq 0.3 \%$
▪ Energy ripple	500 V rms
▪ Beam current	0.5 A DC
▪ Duty factor (averaged over 8 h)	95 %
▪ Electron angles in the cooling section (averaged over time, beam cross section, and cooling section length), rms	≤ 0.2 mrad

All design parameters have been met

Beam quality: Electron angles in the cooling section

Component	Upper limit, μrad	Present estimation, μrad	Diagnostics	Comments
Temperature	90	70	OTR + pepper pot	
Aberrations	90	50 ≤ 30	Simulated BPMs	@ 1 mm (rms)
Envelope scalloping	100	120	Movable orifices (scrapers)	For the 0.5 A beam boundary at 10^{-5} level of losses
Dipole motion caused by magnetic field imperfections	100	40	Magnetic measurements + BPMs	
Beam motion	50	40	BPMs	With a slow feedback
Drift velocity	20	20	Calculated	For $I=0.5$ A
Total	200*	160		

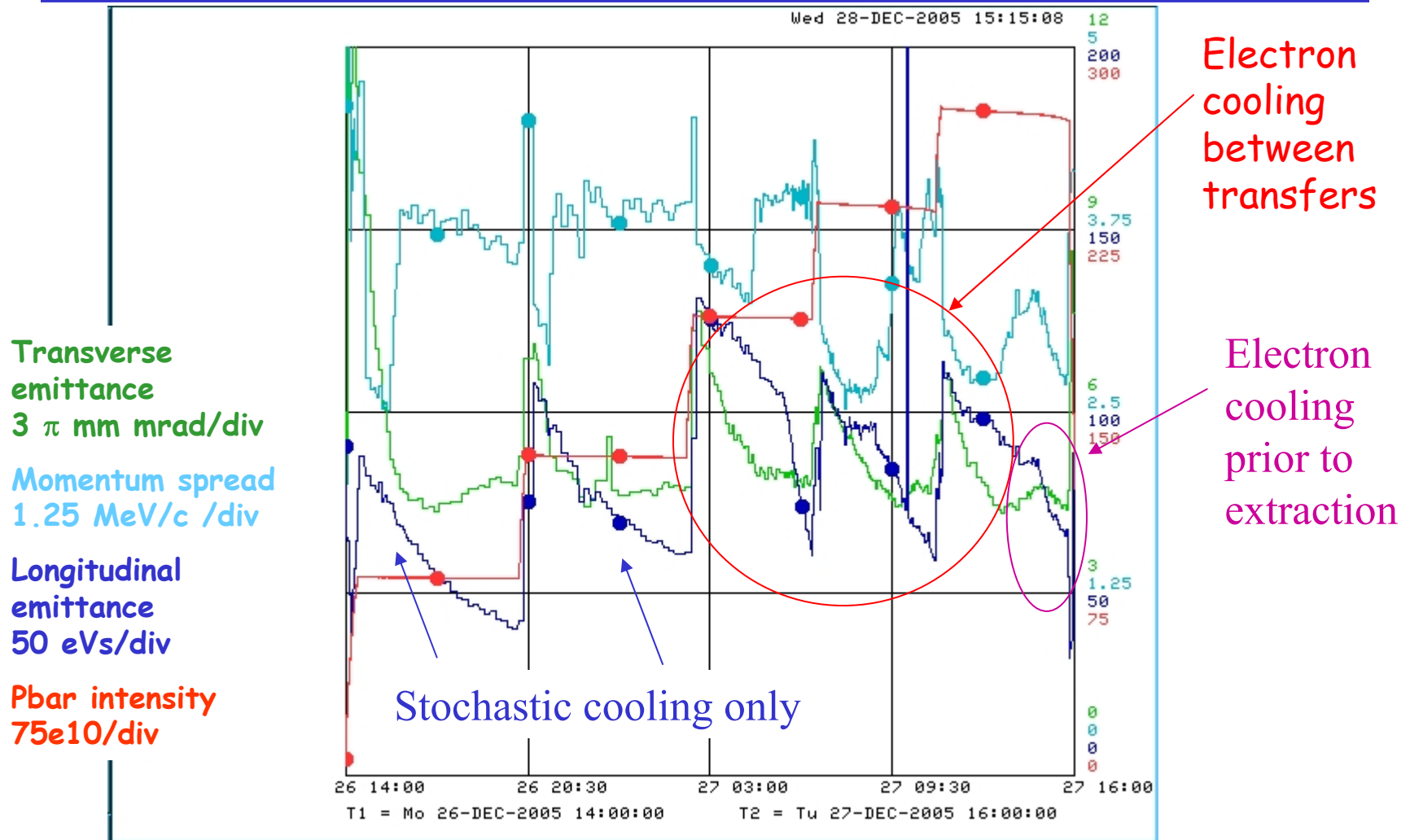
**Angles are added in quadrature*

Electron cooling in operation

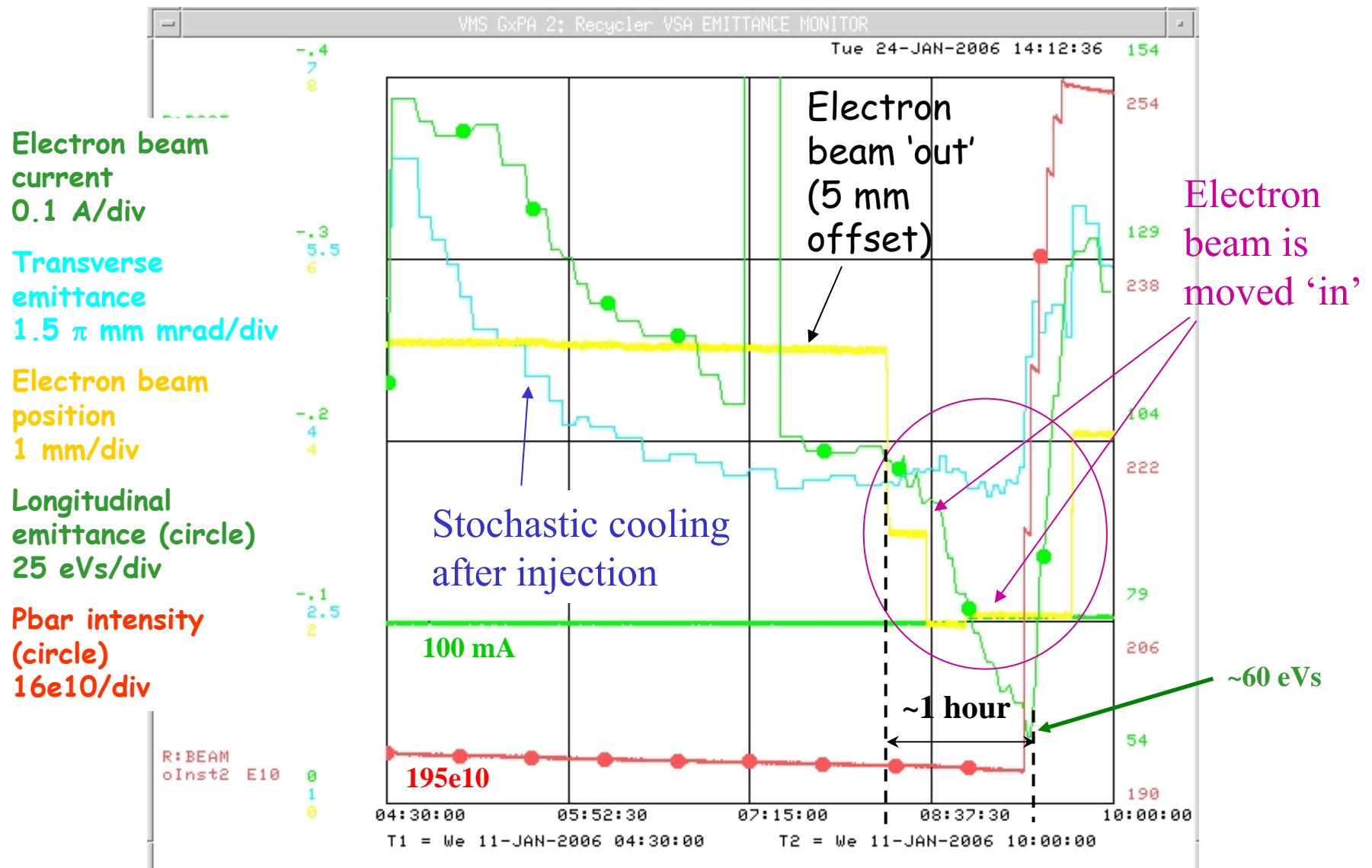
- In the present scheme, electron cooling is typically not used for stashes $< 200e10$
- Over $200e10$ stored
 - Electron cooling used to 'help' stochastic cooling maintain a certain longitudinal emittance (i.e. low cooling from electron beam) between transfers or shot to the TeV
 - ~1 hour before setup for incoming transfer or shot to the TeV, electron beam adjusted to provide strong cooling (progressively)

This procedure is intended to maximize lifetime

Electron cooling in operation (cont')



Electron cooling between transfers/extraction



Control of the cooling rate

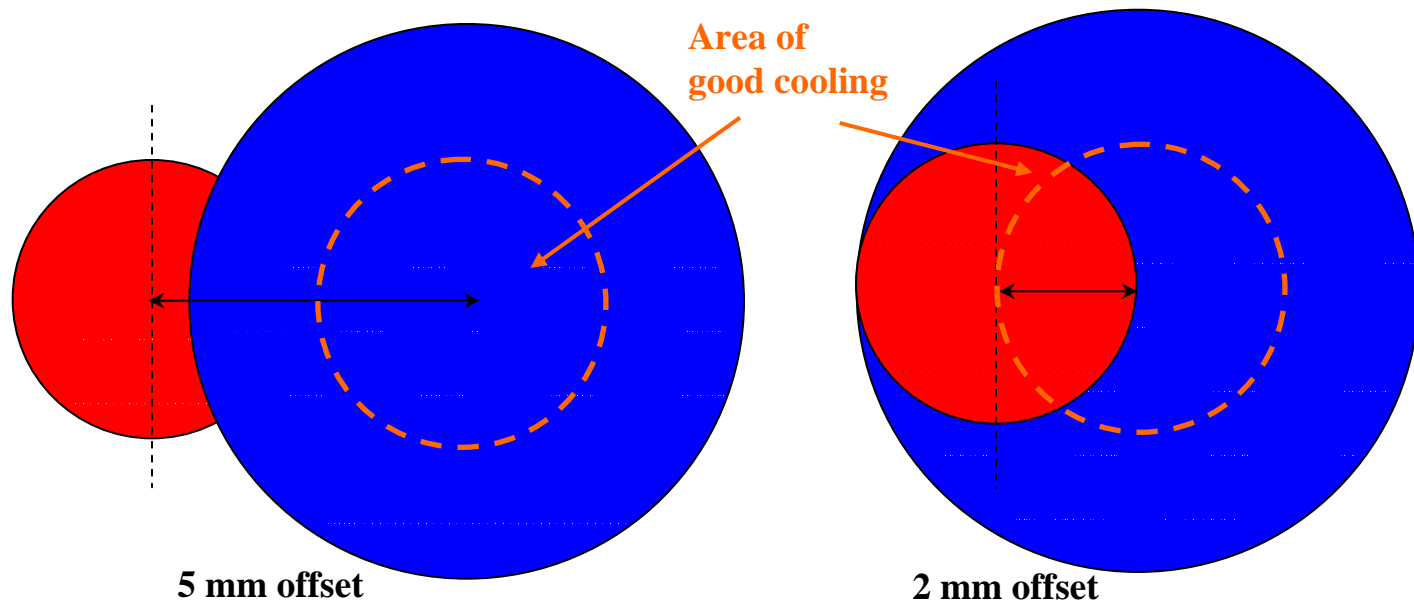
■ Two 'knobs'

➤ Electron beam current

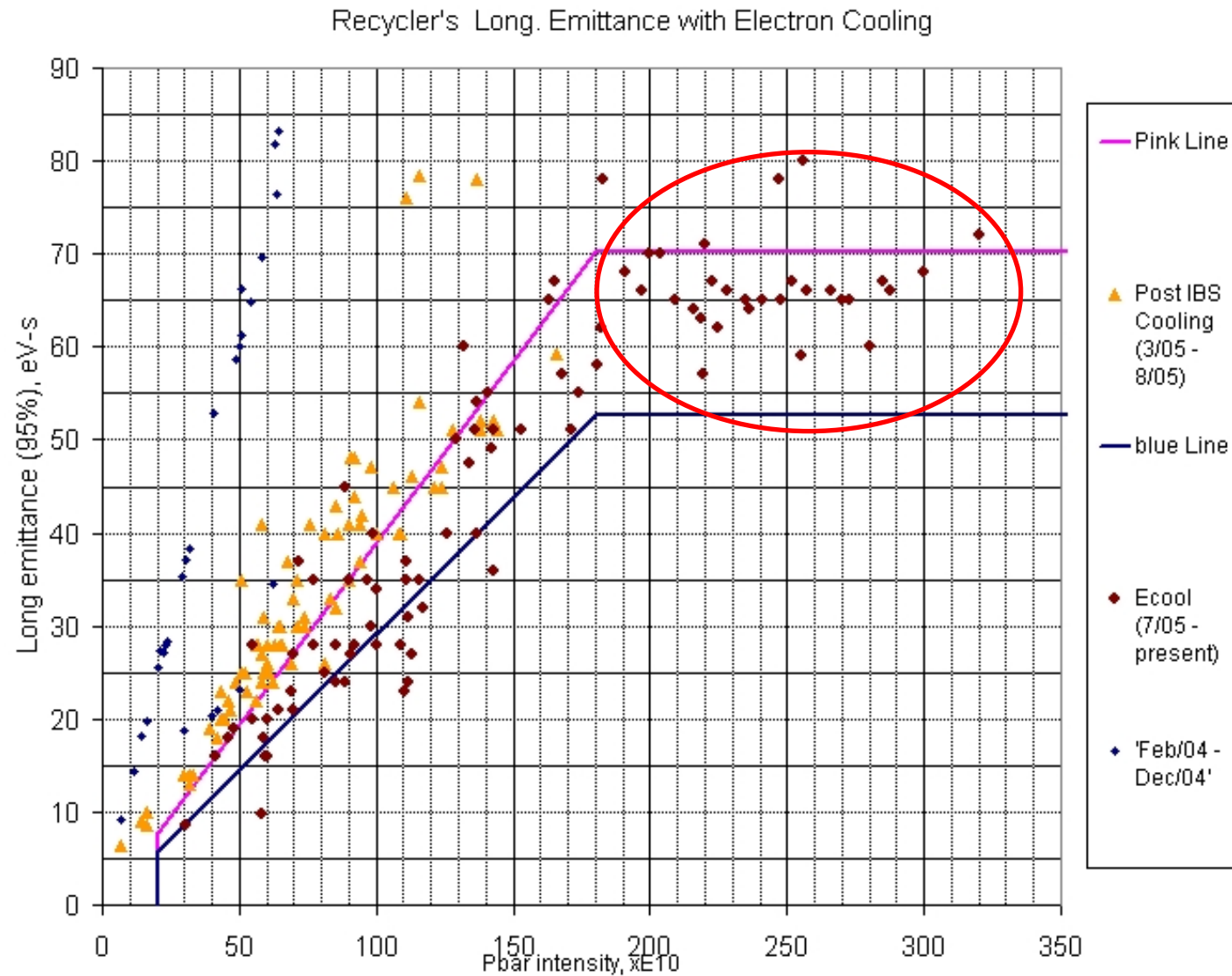
- Beam stays on axis
- Dynamics of the gun varies between low and high currents
- Hence, changing the beam current also changes the beam size and envelope in the cooling section

➤ Electron beam position

- 'Regulation' is obtained by bringing the pbar bunch in an area of the beam where the angles are low



Present Recycler performance with electron cooling

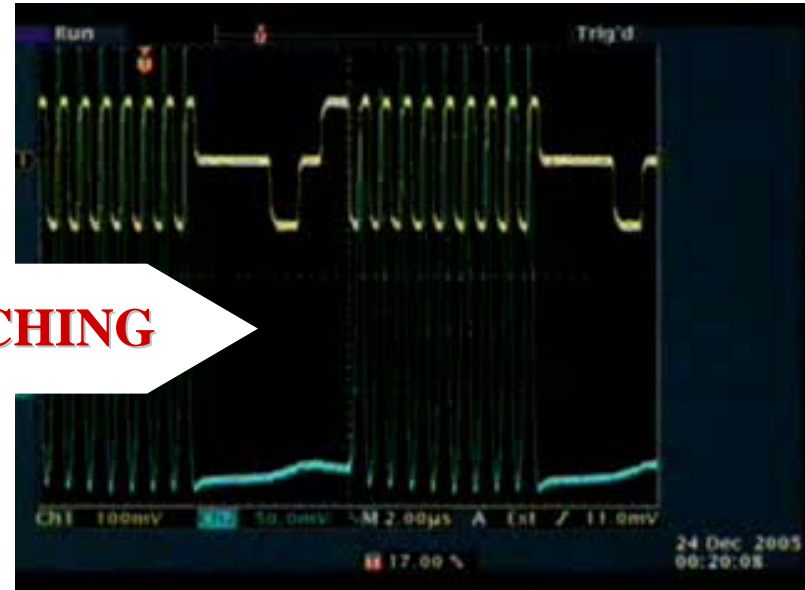


Issues related to electron cooling and large stacks

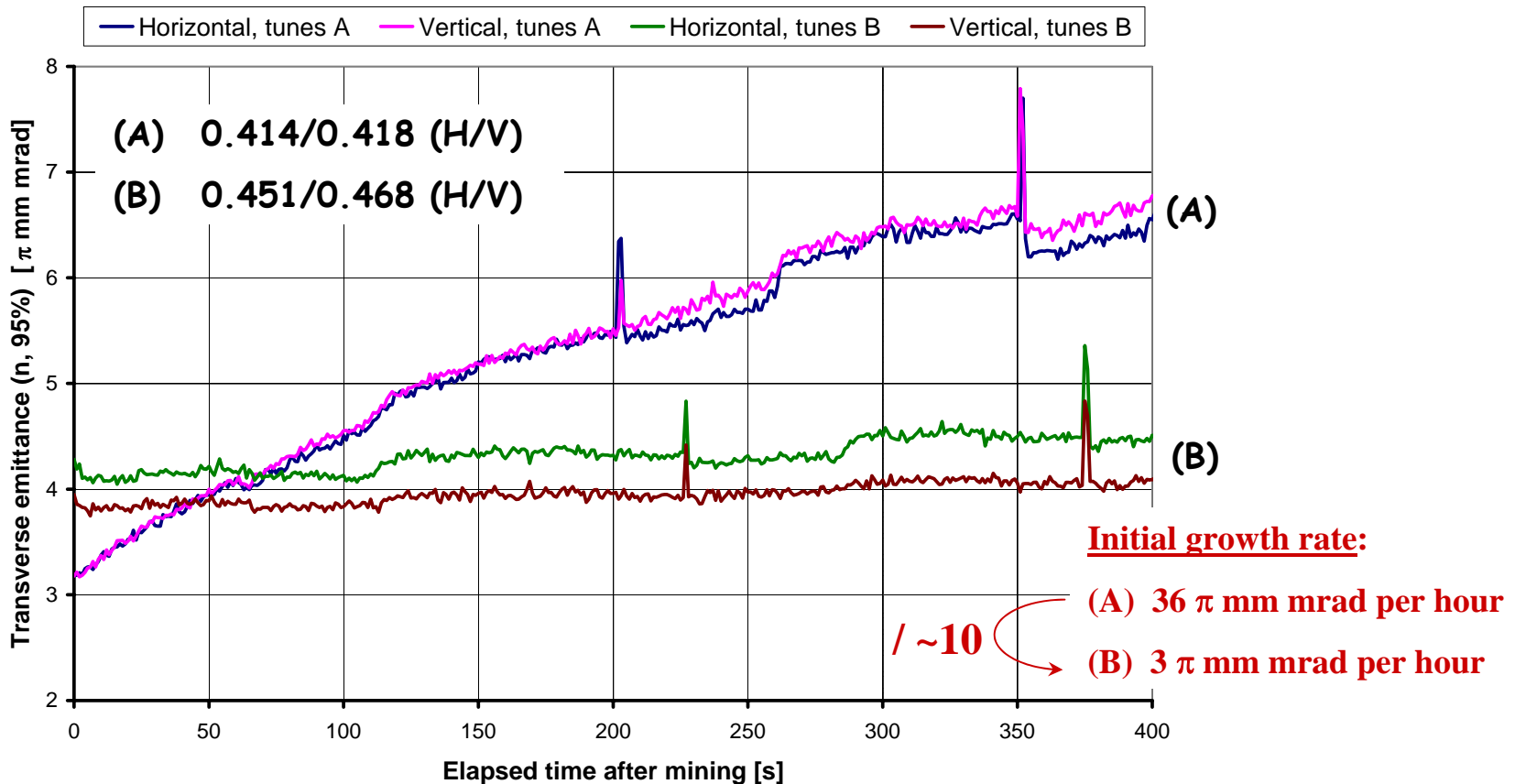
- Since started to use the electron beam for cooling, we have dealt with two main problems
 - Transverse emittance growth
 - After bunching
 - Lifetime degradation
 - When the beam is turned on and/or moved towards the axis (i.e. strong cooling)



BUNCHING

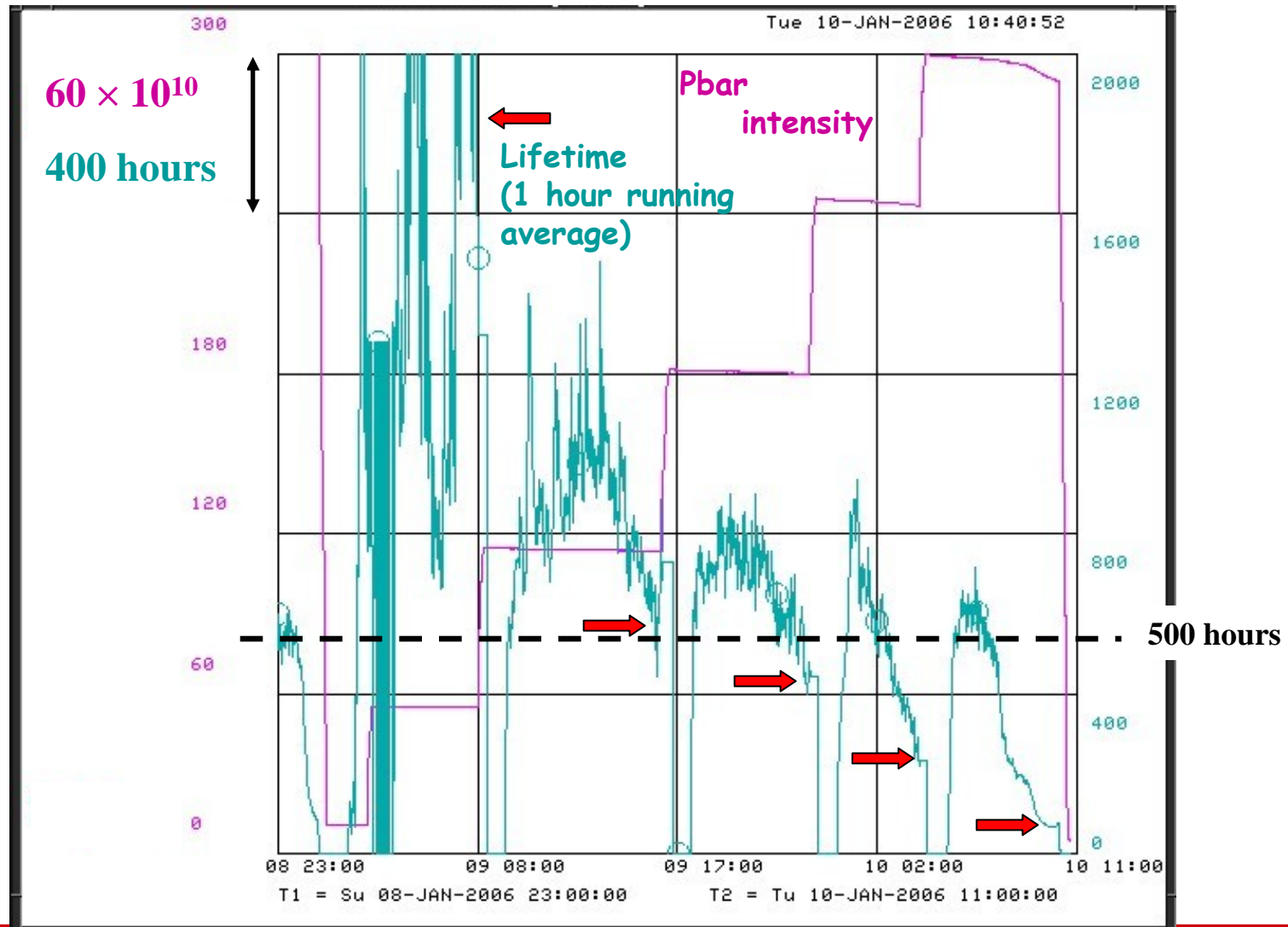


Emittance growth during mining

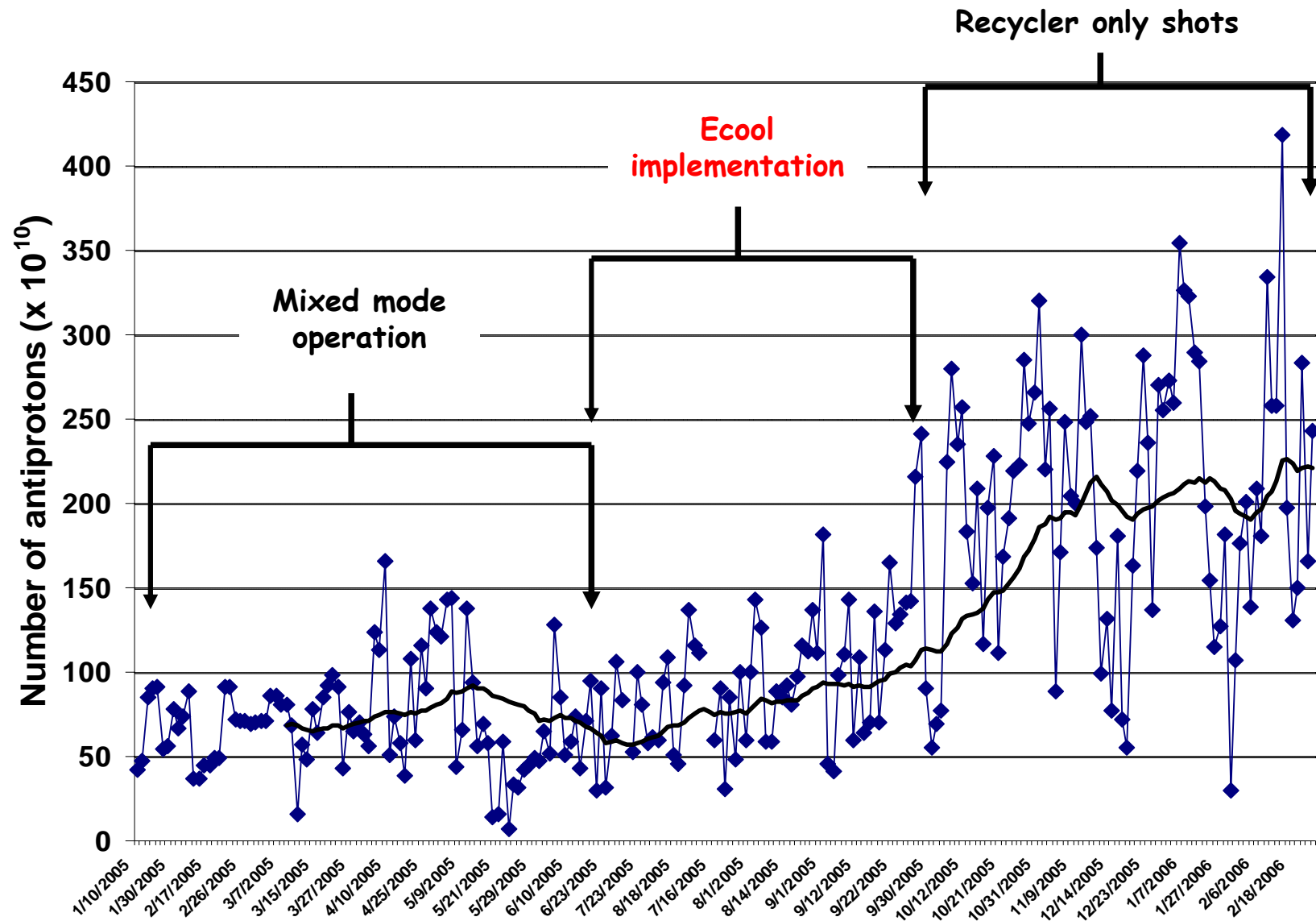


- Emittance growth likely due to a quadrupole instability
 - Growth rate $\propto \kappa_{xy} I_p I_p$, (κ_{xy} coupling parameter)
 - Increase tune split to reduce κ_{xy}

Lifetime degradation throughout a store



Evolution of the number of antiprotons available from the Recycler (~1 year period)



Conclusion

- Fermilab has a unique **operational** electron cooling system for cooling of 8.9 GeV/c antiprotons
 - Since the end of August 2005, electron cooling is being used on (almost) every Tevatron shot
 - Increases of stash sizes are a direct consequence of the ability to cool the beam efficiently (**current record 370e10**)
 - Electron cooling allowed for the latest advances in the TeV peak luminosity (**current record 177e30**)
- Lifetime issue now limits the maximum number of anti-protons that the Recycler can stored
 - Primary focus